JACC Vol. 20, No. 1
July 1992:135–43

Frequency Versus Time Domain Analysis of Signal-Averaged Electrocardiograms. II. Identification of Patients With Ventricular Tachycardia After Myocardial Infarction

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Late potentials detected by the time domain signal-averaged electrocardiogram (ECG) are a well established marker for ventricular tachycardia in patients after a myocardial infarction, but the value of frequency domain analysis of the signal-averaged ECG in identifying these patients remains controversial. This study compared the results of time domain, frequency domain and spectral temporal mapping analyses of the signal-averaged ECG in 30 postinfarction patients with spontaneous sustained ventricular tachycardia and in 30 postinfarction patients without ventricular tachycardia matched for age, gender and infarct site. No patient with bundle branch block was included.

Time domain signal-averaged ECG indexes were significantly different in patients with and without ventricular tachycardia ($p < 0.001$). Frequency domain results were not consistently different between these groups. The values of the normality factor of spectral temporal mapping were significantly lower in patients with ventricular tachycardia ($p < 0.04$). Results of the time domain signal-averaged ECG were abnormal in 22 patients with ventricular tachycardia (73%) but in only 3 control patients (10%) ($p < 0.001$). Spectral temporal mapping results were abnormal in 21 patients with ventricular tachycardia (70%) compared with 12 control patients (40%) ($p < 0.04$). When the optimal numeric values of dichotomy points were computed for patient stratification at different sensitivity levels, time domain analysis identified patients with ventricular tachycardia with significantly fewer false positive results than were obtained with either frequency analysis or spectral temporal mapping.

It is concluded that frequency domain analysis and spectral temporal mapping of the signal-averaged ECG did not improve the identification of postinfarction patients with ventricular tachycardia and without bundle branch block.

(J Am Coll Cardiol 1992;20:135–43)

Late potentials, recorded noninvasively from the body surface and identified by time domain analysis of the signal-averaged electrocardiogram (ECG), are an established marker for sustained ventricular tachycardia in patients after myocardial infarction (1,2). Although the value of the time domain signal-averaged ECG in identifying patients with ventricular tachycardia has been well documented (1,2), the role of frequency analysis and spectral temporal mapping is not well established (3–10). These techniques are believed to offer advantages over time domain analysis (7,11). For example, patients with bundle branch block need not be excluded, low amplitude signals hidden within the terminal portion of the QRS can be detected and no noise-dependent algorithm for identification of late potentials is used. Although some investigators (3–6,8) demonstrated the usefulness of spectral analysis in identifying patients with ventricular tachycardia, others (9,10) failed to confirm such results. Differences in signal processing and in definition of abnormal results accounted in part for these discrepancies.

The aim of this study was to compare time domain analysis with frequency domain analysis and spectral temporal mapping of the signal-averaged ECG in postinfarction patients with and without ventricular tachycardia, with use of commercially available equipment and software.

Methods

Study patients. The study group consisted of 60 postinfarction patients classified in two groups. *Group I (tachycardia group)* consisted of 30 patients with a documented spontaneous ventricular tachycardia (28 men, 2 women, 60 ± 9 years old, 15 with anterior infarction, 15 with inferior infarction), in whom clinical sustained ventricular tachycardia was inducible at electrophysiologic study. Patients with bundle branch block were not included and no patient was receiving antiarrhythmic medication at the time of the study.

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Manuscript received August 26, 1991; revised manuscript received December 18, 1991, accepted January 3, 1992.

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0735-1097/92/$5.00

The interval from the acute infarction to the first episode of spontaneous sustained ventricular tachycardia was 29 ± 30 months (range 25 days to 216 months); in seven patients this interval was >24 months. The interval from acute infarction to the signal-averaged ECG recording was 43 ± 53 months. In all patients the signal-averaged ECG was recorded after the first spontaneous episode of ventricular tachycardia.

Group 2 (control group) consisted of 30 postinfarction patients without any arrhythmic event during a follow-up period of ≥2 years (mean 26 ± 7 months). These patients were matched in age, gender and infarct site with the patients in Group 1 and were selected without knowledge of the results of the signal-averaged ECG. In particular, standard QRS duration was not used to match the groups. Patients with conduction abnormalities (standard QRS duration >120 ms) were not included and no patient was receiving antiarrhythmic medication at the time of the signal-averaged ECG recording. In this group recordings were performed before hospital discharge (day 5 to 11) after acute infarction.

All patients gave written informed consent for the study and the protocol of the study was approved by the local Ethics Committee.

Signal-averaged electrocardiography. *Acquisition.* The signal-averaged ECGs were recorded from the X, Y and Z orthogonal leads with use of an Arrhythmia Research Technology, model 1200 EPX recorder. A mean of 204 cardiac cycles (range 120 to 470 beats) were averaged and the noise level of the time domain signal-averaged ECG at a filter setting of 25 Hz varied between 0.2 and 0.5 μV. The signal-averaged ECG recordings were stored and subsequently analyzed (FFT-Plus software, Arrhythmia Research Technology [12]); all measurements and computations were made automatically without manual intervention.

Analysis. The time domain, frequency domain and spectral temporal mapping analyses were performed simultaneously on the same signal-averaged ECG recording. Time domain analysis of the signal-averaged ECG was performed at high-pass filter settings of 25 and 40 Hz with use of a bidirectional four-pole Butterworth filter. After amplification, averaging and filtering, the signals were combined into a vector magnitude $\sqrt{(x^2 + y^2 + z^2)}$ and three conventional time domain indexes were calculated: duration of the total QRS complex, duration of the low amplitude (<40 μV) signals of the terminal portion of the QRS complex and the root-mean-square voltage of the last 40 ms of the QRS complex. In addition, the root-mean-square voltage of the first 40 ms of the QRS complex was calculated (13). Original recordings are presented in the upper panel of Figure 1.

The two-dimensional frequency domain analysis (also termed spectral analysis) of the signal-averaged ECG was performed with use of fast Fourier transformation. A Blackman-Harris window was used to reduce spectral leakage from edge discontinuities. The analysis was performed at five different settings (methods 1 to 5), reported to be useful by others (4–6,8,12). These methods differed in the combination of the frequency band associated with late potentials or ST segment and in the duration and localization of the analyzed ECG segment. In each method results were expressed as 1) the energy of a certain area, determined by the method, characteristic for late potentials; and 2) the area ratio between this area and the area containing frequencies typical for the ST segment or (method 4) the total area studied. The results were multiplied by 10^4. Values were compared for each orthogonal lead, for the composite lead and for the arithmetic mean of the orthogonal leads (mean X, Y, Z). The details of methods 1 to 5 are presented in Table 1.

Spectral temporal mapping of the signal-averaged ECG used fast Fourier transform analysis and was performed by analyzing 25 overlapping 80-ms segments in 2-ms steps. The first segment began 20 ms before the end of the standard QRS complex. The mean adjustment was set at 0 to eliminate any ST segment elevation or depression. The data were multiplied by a Blackman-Harris window. Results of spectral temporal mapping were expressed as a factor of normality. This factor was calculated on the basis of a reference spectrum that was the average of the five most distal segments (that is, spectra 21 to 25). Once this was established, two mathematic computations were performed for the frequencies between 40 and 140 Hz. The first value derived was the correlation coefficient of the frequency content of each of the 25 spectra as compared with the reference spectrum. The second derivative was based on the area under the curve for each spectrum as compared with the reference spectrum. Examples of spectral temporal maps are presented in the lower panel of Figure 1.

Standard criteria for late potentials. The results of the time domain signal-averaged ECG were considered abnormal when at least two or three conventional variables were beyond the normal range: total QRS duration >120 ms; duration of the low amplitude (<40 μV) signals >40 ms; and root-mean-square voltage of the last 40 ms of the QRS complex <25 μV at a 25-Hz filter setting (1), and >114 ms, >38 ms and <20 μV, respectively, at a 40-Hz filter setting (14). The results of spectral temporal mapping were considered abnormal when the factor of normality was <30% in any lead (7). The results of the two-dimensional frequency domain analysis were not classified as normal or abnormal because the criteria for abnormality have not been established.

Optimal identification of patients with ventricular tachycardia. The success of the time domain, two-dimensional spectral and spectral temporal mapping analyses in identifying patients with ventricular tachycardia was also examined independently of the diagnostic criteria. Many different dichotomy points were selected, so that the corresponding diagnosis of positive signal-averaged ECG results selected 1, 2, . . ., 30 patients with true positive results (that is, tachycardia). Also, for each number of patients with a true positive result, the dichotomy limits were selected, so that the diagnosis of positive signal-averaged ECG results selected the minimal number of patients with a false positive

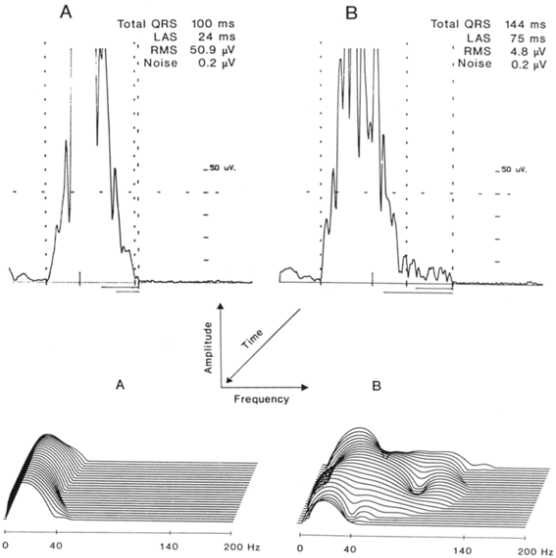

Figure 1. Time domain and spectral temporal mapping recordings from a control patient (**A**) and from a patient with ventricular tachycardia (**B**). The **upper panel** shows the time domain analysis. In the control patient (**A**) the recording is normal, whereas in the patient with ventricular tachycardia (**B**) all time domain indexes are abnormal: late potentials are clearly visible at the end of the QRS complex and in the ST segment. The **lower panel** shows the spectral temporal maps obtained from the same patients. The frequency axis, ranging from 0 to 200 Hz, is horizontal, the amplitude axis is vertical and the time axis is diagonal. The cutoff level is 0 dB. In the control patient (**A**) there was no frequency content between 40 and 140 Hz and the factor of normality was 92%. In the patient with ventricular tachycardia, high frequency components are present in the first 21 segments, whereas the last four segments show only low frequency components characteristic for the ST segment. The normality factor is 9%. LAS = low amplitude signals; RMS = root-mean-square voltage of the last 40 ms of the QRS complex; Total QRS = total QRS duration.

result (that is, no tachycardia). In other words, for each number of possible patients with a true positive result (1, 2, . . ., 30), dichotomy limits were found that yielded this number of true positive results and the fewest possible false positive results. For each of time domain, frequency domain and spectral temporal mapping this analysis resulted in a graph indicating the minimal achievable number of patients with a false positive result for each number of patients with a true positive result.

For the time domain data, this procedure was applied four times with use of 1) three conventional indexes at 25 Hz; 2) three conventional indexes and the root-mean-square voltage of the initial 40 ms of the QRS complex at 25 Hz; 3) three conventional indexes at 40 Hz; and 4) three conventional indexes and the root-mean-square voltage of the initial 40 ms of the QRS complex at 40 Hz. In each case the results of the signal-averaged ECG were considered abnormal if any two variables used had an abnormal value according to the particular set of selected dichotomy points.

For each of five two-dimensional spectral methods, this

Table 1. Methods of Two-Dimensional Frequency Domain Analysis

Method	Segment: Onset	Segment: Duration (ms)	Frequency Band Typical for LPs (Hz)	Area Ratio Calculation (Hz)
1	20 ms before sQRS offset	120	20 to 50	20 to 50/0 to 20
2	20 ms before sQRS offset	120	60 to 120	60 to 120/0 to 30
3	60 ms after sQRS onset	140	20 to 50	20 to 50/0 to 20
4	Vector magnitude <40 μV*	120	60 to 120	60 to 120/0 to 120
5	sQRS onset	140	20 to 50	20 to 50/0 to 20

*The onset of the segment analyzed in method 4 is at the point where vector-summed QRS forces last decreased to <40 μV at a 25-Hz filter setting. LPs = late potentials; sQRS = standard QRS.

procedure was performed separately for area energies (four values obtained in leads X, Y and Z and the composite lead) and for area ratios (five values obtained in leads X, Y and Z, the composite lead and the mean of leads X, Y and Z). In all, 10 sets of values were evaluated. For each set the following possibilities were further considered: 1) Either the same dichotomy point was introduced for all four or five indexes or individual dichotomy points were considered for individual variables; and 2) a positive result of the signal-averaged ECG was considered if any one or any two of all four or five indexes exceeded the selected dichotomy point. The combination of these options provided four possibilities.

The numeric values of normality factors of spectral temporal mapping were examined with use of the same four possibilities: the same or individual dichotomies for individual leads and the positive findings diagnosed when the normality factor of any one or any two leads was lower than the selected dichotomy point.

Statistical methods. Continuous variables are presented as the mean value ± SD. Unpaired *t* tests were used to compare the numeric values of individual signal-averaged ECG variables in both groups. The chi-square test with Yates correction and the Fisher exact test were used to compare the proportions between true and false positive and true and false negative results corresponding to the standard diagnostic criteria of time domain and spectral temporal mapping analysis.

The relations between the true positive and minimal false positive results, achieved with different methods of signal-averaged ECG analysis, were statistically compared: 1) For three arbitrarily selected values of sensitivity (80%, 87% and 93%) corresponding to 24, 26 and 28 patients with a true positive result, the ratios of (false positive)/(true negative) achieved with the values of the time domain variables were

Table 2. Results of Time Domain Analysis of the Signal-Averaged Electrocardiogram at 25 Hz

Variable	VT	Control	p Value*
Total QRS (ms)	141.7 ± 28	101.6 ± 13	0.001
LAS (ms)	50 ± 22	24.5 ± 12	0.001
RMS of last 40 ms (μV)	20.3 ± 20	74.8 ± 60	0.001
RMS of first 40 ms (μV)	87.6 ± 47	140.7 ± 89	0.006

*Statistical significance of the difference between the two patient groups (*t* test). Values are expressed as mean value ± SD of the indexes of the time domain analysis of the signal-averaged electrocardiogram in the patients with ventricular tachycardia (VT) and in the control patients. LAS = duration of the low amplitude signals <40 μV; RMS = root-mean-square voltage.

Table 3. Results of Five Methods of Two-Dimensional Frequency Analysis of the Signal-Averaged Electrocardiogram

		Energy of Area			Area Ratio		
Method	Lead	VT	Control	p Value	VT	Control	p Value*
1	X	91.9 ± 46	69.9 ± 25	0.026	6,201 ± 7,947	3,356 ± 2,080	NS
	Y	80.9 ± 34	83.1 ± 37	NS	5,607 ± 6,362	3,781 ± 2,835	NS
	Z	55.9 ± 25	53.7 ± 28	NS	2,600 ± 2,350	2,169 ± 1,721	NS
	Mean XYZ	—	—	—	487 ± 405	310 ± 147	0.03
	Composite	67.4 ± 37	60.1 ± 24	NS	3,127 ± 2,578	2,302 ± 1,263	NS
2	X	40.8 ± 24	34.8 ± 20	NS	1,963 ± 1,728	1,567 ± 1,247	NS
	Y	33.3 ± 23	34.4 ± 22	NS	1,624 ± 1,900	1,501 ± 1,254	NS
	Z	18.1 ± 14	19.7 ± 13	NS	673 ± 641	716 ± 555	NS
	Mean XYZ	—	—	—	142 ± 109	126 ± 65	NS
	Composite	27.7 ± 23	19.8 ± 9	NS	1,045 ± 982	704 ± 381	NS
3	X	98.7 ± 44	74.6 ± 42	0.03	5,487 ± 4,339	3,566 ± 2,945	0.05
	Y	83.1 ± 27	91.9 ± 45	NS	4,030 ± 2,342	4,941 ± 4,295	NS
	Z	63.8 ± 42	56.7 ± 41	NS	2,820 ± 2,529	2,401 ± 2,075	NS
	Mean XYZ	—	—	—	411 ± 214	364 ± 230	NS
	Composite	81.1 ± 37	64.3 ± 39	NS	3,834 ± 2,455	2,743 ± 2,398	NS
4	X	39.8 ± 22	36.4 ± 24	NS	1,155 ± 583	1,144 ± 776	NS
	Y	31.5 ± 22	32.6 ± 20	NS	951 ± 703	972 ± 595	NS
	Z	22.2 ± 16	21.2 ± 16	NS	649 ± 466	610 ± 428	NS
	Mean XYZ	—	—	—	92 ± 44	91 ± 40	NS
	Composite	30.6 ± 28	20.1 ± 11	NS	851 ± 723	596 ± 311	NS
5	X	114.1 ± 20	125.6 ± 31	NS	5,979 ± 1,917	7,937 ± 3,922	0.018
	Y	115.7 ± 21	134.1 ± 39	0.027	6,440 ± 2,586	9,684 ± 6,143	0.011
	Z	101.5 ± 22	114.9 ± 28	0.044	5,183 ± 1,887	6,759 ± 3,307	0.028
	Mean XYZ	—	—	—	587 ± 146	813 ± 254	0.000
	Composite	114.3 ± 27	139.3 ± 27	0.001	6,184 ± 2,266	8,974 ± 3,682	0.001

*Statistical significance of the difference between the two patient groups (*t* test). Values are expressed as mean value ± SD of the indexes of spectral analysis in the patients with ventricular tachycardia (VT) and in the control patients. For each method of analysis, the results are shown for individual leads. The values of area ratios were multiplied by 10^4. For the mean XYZ lead only area ratios were calculated.

Table 4. Results of the Spectral Temporal Mapping of the Signal-Averaged Electrocardiogram

Lead	VT	Control	p Value*
X	53.8 ± 37	62.2 ± 26	0.042
Y	44.4 ± 30	67.0 ± 30	0.005
Z	46.7 ± 36	70.9 ± 28	0.006
Composite	40.4 ± 31	56.9 ± 30	0.040

*Statistical significance of the difference between the two patient groups (*t* test). Values are expressed as mean value ± SD of the normality factor (in %) of spectral temporal mapping in the patients with ventricular tachycardia (VT) and in the control patients.

compared (Fisher exact test) with the same ratios achieved with the values of the variables of other methods for signal-averaged ECG analysis; 2) for each level of sensitivity, the minimal false positive values achievable by varying the dichotomy points (see the previous section) were used in this statistical evaluation; and 3) in all statistical tests, a two-tailed p value < 0.05 was required for statistical significance.

Results

Numeric values of the time domain, spectral and spectral temporal mapping analyses. Of the time domain variables, the total QRS and low amplitude signal durations were significantly longer and the root-mean-square voltages of the first and the last 40 ms of the QRS complex were significantly lower in patients with ventricular tachycardia than in control patients. Results obtained at 25 Hz are presented in Table 2; results were similar at the 40-Hz setting.

The detailed results of two-dimensional frequency domain analysis are presented in Table 3.

In methods 1 to 4, examining the final portion of the QRS complex and the ST segment, the energies of areas characteristic for late potentials and the area ratios were higher in patients with ventricular tachycardia than in control patients in 28 measurements, whereas the opposite was true of the remaining eight measurements (six in lead Y and two in lead Z). With use of method 5, examining the entire QRS complex, the energy of the area between 20 and 50 Hz and

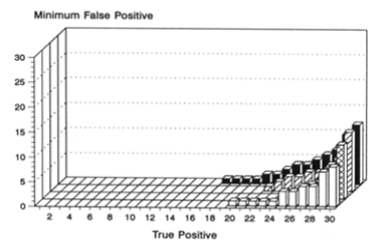

Figure 2. Plots showing the minimal number of false positive cases obtained for different numbers of true positive cases when using the results of time domain analysis to identify the patients with ventricular tachycardia. The **rows of bars** correspond to the diagnostic strategies (see text for details): **closed bars** = standard analysis at 40 Hz; **cross-hatched bars** = standard analysis combined with the root-mean-square voltage of the first 40 ms of the QRS complex (25-Hz filter setting); **open bars** = standard analysis combined with the root-mean-square voltage of the initial 40 ms of the QRS complex (40-Hz filter setting); **hatched bars** = standard analysis at 25 Hz.

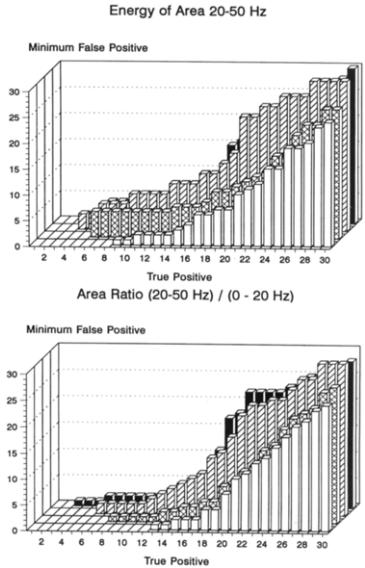

Figure 3. The plots show the minimal number of false positive cases obtained for different numbers of true positive cases when using the results of spectral analysis (method 1) to identify patients with ventricular tachycardia. **The upper part** corresponds to the analysis of the values of area energies, the **lower part** to the analysis of the values of area ratios. The **rows of bars** correspond to the diagnostic strategies (see text for details): **closed bars** = ≥2 indexes abnormal plus 1 dichotomy limit; **cross-hatched bars** = ≥1 indexes abnormal plus 4 or 5 individual dichotomy limits; **open bars** = positive result diagnosed as ≥2 indexes being abnormal with use of 4 or 5 individual dichotomy limits for individual leads; **hatched bars** = ≥1 indexes abnormal plus 1 dichotomy limit.

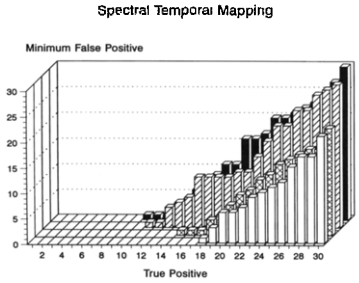

Figure 4. Plots showing the minimal number of false positive cases obtained for different numbers of true positive cases when using the results of spectral temporal mapping of the signal-averaged ECG to identify the patients with ventricular tachycardia. The **rows of bars** correspond to the diagnostic strategies: **closed bars** = ≥2 values of normality factor abnormal plus 1 dichotomy limit (see text for details); **cross-hatched bars** = ≥1 values of normality factor abnormal plus 4 individual dichotomy limits; **open bars** = positive result diagnosed as ≥2 values of normality factor being abnormal with use of 4 individual dichotomy limits for individual leads; **hatched bars** = ≥1 values of normality factor abnormal plus 1 dichotomy limit.

the area ratio obtained by dividing this area by the area from 0 to 20 Hz were consistently lower in all leads in patients with ventricular tachycardia than in control patients; this difference reached statistical significance in all but one measurement.

When spectral temporal mapping was performed, the values of the factor of normality were significantly lower in all leads in patients with ventricular tachycardia than in control patients (Table 4).

Standard criteria for late potentials. An abnormal time domain signal-averaged ECG at the 25-Hz filter setting was recorded in 22 patients with ventricular tachycardia (73%) compared with 3 control patients (10%) ($p < 0.001$) and in 24 patients from the tachycardia group (80%) compared with 7 control patients (23%) ($p < 0.001$) when a 40-Hz filter setting was used. Spectral temporal mapping was abnormal in 21 patients with ventricular tachycardia (70%) compared with 12 control patients (40%) ($p < 0.04$).

Optimal identification of patients with ventricular tachycardia. Figures 2, 3 and 4 show the numbers of minimal false positive results obtained for different numbers of true positive results when using time domain, frequency domain (method 1 as an example) and spectral temporal mapping analyses. For each set of data and for each strategy of their analysis (see the Methods section), the figures contain one graph showing dependency between the true positive and minimal false negative cases.

For each number of true positive cases, these minimal false negative cases corresponded to the optimal selection of dichotomy limits. With spectral temporal mapping, for example (see the middle of Fig. 4), we were able to select four such dichotomy points for normality factors of leads X, Y and Z and the composite lead, so that when positive results were based on normality factors of two or more leads being positive, the stratification selected 18 patients with a true positive result and only 1 patient with a false positive result. However, when positive results were based on normality factors of one or more leads being positive, no dichotomy limits could have been selected that, together with 18 true positive cases, would have stratified fewer than three false positive cases. A still poorer result was achieved when we tried to select the same dichotomy value (that is, the normal range) for the normality factors for all leads. Then the minimal value of the false positive result (still true positive for 18) was 10 and 11, respectively, when the positive result was based on the positivity of any one or any two leads.

In these figures, for any number of true positive results the minimal number of false positive results obtained with frequency analysis or spectral temporal mapping was higher than that obtained with the time domain analysis.

The minimal number of false positive results and maximal specificity for identifying patients with ventricular tachycardia obtained by different types of signal-averaged ECG analysis for three sensitivity levels (80%, 87% and 93%) are compared in Table 5. The specificity values obtained with time domain analysis were consistently higher than those obtained by frequency analysis at all presumed sensitivity levels. These differences reached statistical significance in all but one (method 5) frequency analysis setting.

Discussion

Study Findings

Time domain analysis. Our results confirm the value, demonstrated by others (1,2), of the conventional time domain signal-averaged ECG in identifying postinfarction patients with ventricular tachycardia. For any number of true positive results, the minimal number of false positive results was higher with use of frequency domain analysis or spectral temporal mapping than with time domain analysis. The identification of patients with ventricular tachycardia was slightly improved by combining the root-mean-square voltage of the initial portion of the QRS complex with three other conventional signal-averaged ECG variables, which is consistent with the findings of Kienzle et al. (13). For example, when 24 patients were identified as having a true positive result, there were no false positive results when conventional time domain indexes were used with the root-mean-square voltage of the initial portion of the QRS complex (at the 25-Hz filter setting), whereas three false positive results were obtained with conventional variables alone. Reduced voltage of the initial part of the QRS complex may represent areas of slow conduction around the postinfarction

Table 5. Comparison of Patient Stratification at Different Sensitivity Levels Based on the Time, Spectral and Spectral Temporal Mapping Analysis of the Signal-Averaged Electrocardiogram

	Sensitivity 80% TP = 24			Sensitivity 87% TP = 26			Sensitivity 93% TP = 28		
	FP	Spec	p	FP	Spec	p	FP	Spec	p
Time domain	0	100	N/A	2	93	N/A	4	87	N/A
Spectral									
Method 1	15	50	10^{-5}	19	37	10^{-5}	20	33	10^{-4}
	14	53	10^{-4}	18	46	10^{-4}	21	30	10^{-4}
Method 2	20	33	10^{-7}	22	27	10^{-6}	23	23	10^{-5}
	19	37	10^{-7}	20	33	10^{-5}	22	27	10^{-5}
Method 3	9	70	0.0019	10	67	0.021	12	60	0.039
	8	73	0.0046	10	67	0.021	12	60	0.039
Method 4	19	37	10^{-7}	20	33	10^{-5}	22	27	10^{-5}
	17	43	10^{-6}	19	37	10^{-5}	21	30	10^{-4}
Method 5	6	80	0.0237	6	80	NS	9	70	NS
	4	87	NS	5	83	NS	8	73	NS
STM	10	67	0.0008	12	60	0.0048	17	43	0.0009

For each spectral method, the first result corresponds to the values of the energy of the area studied, the second result to the area ratio. FP = minimal number of false positive results; N/A = not applicable; p = comparison between time domain analysis and other methods (Fisher exact test.); Spec = maximal specificity; STM = spectral temporal mapping; TP = true positive results.

scar in the interventricular septum, especially in patients with anterior infarction (13). However, this variable has not been widely used in time domain analysis, and its value for improving identification of postinfarction patients with ventricular tachycardia needs further clarification.

Frequency domain analysis. Frequency domain analysis appeared less effective than the time domain signal-averaged ECG in identifying patients with ventricular tachycardia. The differences between patients with and without ventricular tachycardia were insignificant in a majority of leads when the two-dimensional frequency analysis of the final portion of the QRS complex (methods 1 to 4) was performed. This observation is in contrast to the results of some previous work (3–6,8) investigating the identical ECG segments and frequency bands used in our study, but it is consistent with the findings of Machac et al. (10), who found frequency domain analysis to be less specific and less sensitive than time domain analysis in identifying patients with ventricular tachycardia. Similarly, Kelen et al. (9) were unable to differentiate postinfarction patients with ventricular tachycardia from control patients with frequency analysis of the signal-averaged ECG. In our study only method 5, assessing the frequency content from the beginning of the QRS complex, yielded significantly different results in patients with and without ventricular tachycardia. The energies of areas characteristic for late potentials and the area ratios were higher in control patients than in patients with ventricular tachycardia, a result consistent with those obtained by Worley et al. (5). However, assuming that late potentials are characterized by high frequency components, the results obtained with method 5 may depict other than effects of late potentials. First, the results might have been influenced by differences between postinfarction patients with and without ventricular tachycardia in the high frequency content within the entire QRS complex. Also, the duration of the analyzed segment of 140 ms is too short in patients whose total QRS duration is >140 ms due to the presence of long late potentials (in our study 14 patients with ventricular tachycardia had a total high gain QRS duration >140 ms). In such cases the late potential extends beyond the analyzed segment.

Spectral temporal mapping. With spectral temporal mapping, we were able to identify patients with ventricular tachycardia, although the sensitivity and specificity of this technique were lower than those obtained with time domain analysis. Spectral temporal mapping yielded more false positive results than did time domain analysis, a factor that may have contributed to these findings. In some cases we believed that a visual inspection of spectral temporal maps was more informative than the values of normality factor alone. However, it is difficult to quantify the results of such visual inspection. Moreover, in other control patients, abnormal values for normality factor were consistent with the results of visual inspection of spectral temporal maps. The main reason for these false positive results may be that the first analyzed segments were located too early, well within the main QRS complex where high frequency components are usually present on the spectral temporal maps.

Overall, our findings are consistent with results of two recent studies (15,16) that showed that in postinfarction patients without bundle branch block time domain analysis of the signal-averaged ECG was more powerful for identifying patients with ventricular tachycardia than was spectral temporal mapping.

There are several possible reasons for the failure of frequency analysis to improve identification of patients with

ventricular tachycardia. Fast Fourier transform has many limitations when applied to a biologic signal (17). Mathematic window functions (such as Blackman-Harris window) are necessary to smooth the windowed data to zero at the boundaries. However, the use of windows to avoid spectral leakage may attenuate the signal of interest. The fast Fourier transform is also very sensitive to the duration of the analyzed segment (9). With this technique precise location of late potentials is difficult and frequency resolution of the short segments is poor. The exact frequencies typical for late potentials have not been defined (18). Many limitations of fast Fourier transform analysis can be overcome by applying autoregressive methods. Recently Haberl et al. (19) showed that top-resolution frequency analysis of the signal-averaged ECG with adaptive frequency determination better identified patients with ventricular tachycardia than did fast Fourier transform analysis. Discordant results between the present study and some other data may relate also to differences in study groups. In contrast to previous studies (3–6,8), we used pair-matched groups because the results of the time domain signal-averaged ECG are significantly influenced by the site of infarction (14) and by patient age (20). Finally, Emmot and Vacek (21) recently reported the lack of short-term reproducibility of the frequency domain signal-averaged ECG using fast Fourier transform analysis, a limitation that can also diminish the value of this method for identifying patients with ventricular tachycardia.

Limitations of the study. Our study group consisted of postinfarction patients without conduction abnormalities. Lindsay et al. (11) showed in patients with bundle branch block that frequency domain analysis is a valuable tool for identifying patients likely to develop ventricular tachycardia. Some other recent reports (22,23) have demonstrated the usefulness of spectral temporal mapping in identifying patients with ventricular tachycardia despite the presence of bundle branch block. Also, in patients with doubtful time domain results (for example, because the noise level is not low enough to unmask the presence of late potentials of very low amplitude), spectral temporal mapping may improve detection of late potentials (24).

The criteria for abnormality of spectral temporal mapping (the normality factor <30% in any lead) were designed by Haberl et al. (7) with use of a Hanning window and 25 segments in 3-ms steps and may not be optimal for the spectral temporal analysis used in the present study. It is also possible that normal values for the factor of normality should take infarct site into account and should vary for different leads, as was suggested in one preliminary report (25).

The signal-averaged ECG recordings in the control group were performed early after the acute phase of infarction, whereas in the tachycardia group they were recorded a mean of 43 months after the acute infarction. This difference could result in overestimation of the prevalence of late potentials in the control group because the incidence and timing of late potentials decrease slightly during the 1st year after infarction (26,27). However, these factors probably did not significantly influence our results because the incidence of late potentials detected by time domain analysis was low in the control group (two patients, 8%).

In seven patients of the tachycardia group the first spontaneous episode of sustained ventricular tachycardia occurred >24 months after acute infarction. Thus, although the mean duration of follow-up in the control group was 26 months (range 24 to 48), we cannot rule out the possibility that some of these patients may develop ventricular tachycardia in the future.

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